Reach of future colliders in probing the structure of the photon

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Abstract

A comparison of the potentials of ep and e^+e^- machines to probe the structure of the photon is performed. In particular, the kinematic reach of a proposed future ep facility, THERA, is compared with those of current colliders, LEP and HERA, and with the proposed linear collider, TESLA. THERA like HERA will use a proton beam of 920 GeV but with an increased electron beam energy of 250 GeV allowing higher scales, $\hat{Q}^2$, and lower values of parton momentum fraction in the photon, x_γ, to be probed.

1   Introduction

The photon - the gauge boson of QED - has, in high energy processes, a "hadronic structure". In deep inelastic scattering, $e\gamma \rightarrow e$ hadrons, the corresponding structure function can be introduced, $F_2^\gamma(x, \hat{Q}^2)$, where $\hat{Q}^2$ is the scale at which the quasi-real photon is probed. At low Bjorken x this structure function is expected to behave like F_2^p, i.e. it increases towards lower x at sufficiently large $\hat{Q}^2$, where $\hat{Q}^2$ is the scale at which the quasi-real photon is probed. Unique expectations for the photon are the logarithmic rise of the structure function, F_2^γ, with the scale $\hat{Q}^2$ and a large quark density at large x ($\sim x_\gamma$). Observations of these phenomena are basic tests of QCD.

In deep-inelastic $e\gamma$ scattering at e^+e^- colliders the scale $\hat{Q}^2$ is given by the virtuality Q^2 of the probing virtual photon whereas in the photoproduction regime ($Q^2 < 1$ GeV^2) in ep collisions and collisions of quasi-real photons, $\gamma\gamma$ scattering, in e^+e^- colliders it is usually given by the transverse momentum p_T of jets or final state particles.

The ep collider, THERA, would offer the opportunity to study the partonic structure of the photon extending the kinematic range in x_γ and $\hat{Q}^2$ over existing colliders (HERA and LEP) by approximately one order of magnitude. At lowest order, x_γ is equal to unity for "direct"

processes (Fig. 1a), whereas "resolved" processes (Fig. 1a), where the photon interacts via its partonic content, are characterised by a smaller value of x_γ. In addition, the photoproduction of particles (hadrons or prompt photons) or jets at high p_T provides complementary information to that from deep-inelastic eγ on the partonic, in particular gluonic (Fig. 1b), content of the quasi-real photon. The photoproduction of dijets, heavy quarks and prompt photons have been studied [1, 2], with the emphasis on the potential of THERA to yield information on the structure of the real photon. The possibility of studying the structure of the virtual photon at THERA has also been considered [3].
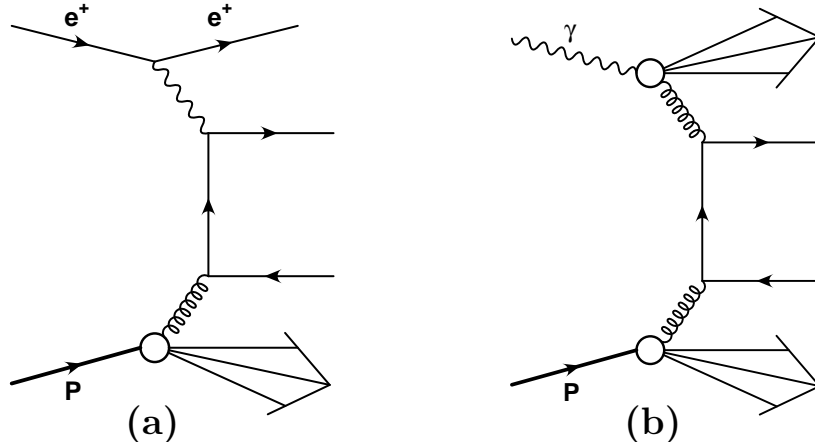

Figure 1: Examples of lowest order (a) direct photon and (b) resolved photon processes in ep collisions.

Good knowledge of the hadronic interactions of a fundamental particle - the photon - is essential for the future high energy physics programme. The present situation is not satisfactory as data for some processes, such as that for the photoproduction of dijets at HERA are not in agreement with existing next-to-leading (NLO) QCD calculations [4, 5]. The agreement for processes involving resolved virtual photons is even more problematic. A proper description of the hadronic interaction of photons is also needed to calculate the Standard Model background in searches for the Higgs particle and other new phenomena at future colliders.

Initially a comparison is made of the kinematic regions accessible at various colliders where the structure of the photon can be tested: LEP, HERA and the future linear collider (TESLA) in the basic e$^+$e$^-$ mode. The aim of this section is to show how THERA can enrich the potential of TESLA in its standard e$^+$e$^-$ mode and so detailed comparisons with photon colliders ($\gamma\gamma$ or eγ modes) are not considered. It is assumed that the energy of the electron beam is 250 GeV and that of the proton beam is 920 GeV.

2 The THERA kinematic region in comparison with other colliders

In considering the benefits of THERA for studying the structure of the photon, all current machines and those of the future are discussed for comparison. The kinematic reach of THERA

($\sqrt{s} \approx 1$ TeV) is compared with those of LEP ($\sqrt{s} \approx 200$ GeV), HERA ($\sqrt{s} \approx 300$ GeV) and a future linear e^+e^- collider, TESLA, ($\sqrt{s} \approx 500$ GeV), where $\sqrt{s}$ denotes the centre-of-mass energy of the colliding primary beams. The nominal ep and e^+e^- options are considered for THERA and TESLA, respectively; the corresponding γp and γe or $\gamma\gamma$ options cover a similar kinematic region with an increased cross section but lower luminosity. Of interest is to consider the minimum x_γ, the range of $\hat{Q}^2$ and the polar angle (rapidity) of the jets in resolved photon events. For comparison the following quantities are introduced, relevant for deep-inelastic $e\gamma$ scattering and resolved photon processes in e^+e^- and ep colliders:

$$Q^2_{\max,\min}|_{e^+e^-} = \frac{W^2_{\max,\min}x_\gamma}{1-x_\gamma}, \qquad \hat{Q}^2|_{ep} \equiv p_T^2 = (y_{\max}E_e e^{\eta_{\max}}x_\gamma)^2 \tag{1}$$

$$x|_{e^+e^-} = \frac{Q^2}{Q^2+W^2}, \quad x_\gamma^{\min}|_{e^+e^-} = \frac{p_T e^{\pm\eta_{CM}}}{2E_e - p_T e^{\mp\eta_{CM}}}, \quad x_\gamma^{\min}|_{ep} = \frac{E_p p_T e^{-\eta_{LAB}}}{2E_e E_p - E_e p_T e^{\eta_{LAB}}}, \tag{2}$$

where W denotes the invariant mass of the hadronic final state. In Fig. 2a, the minimum photon momentum fraction, $x_\gamma^{\min}$, is shown for a given transverse momentum, p_T, ($= E_T$ for massless particles) of 10 GeV, as a function of the rapidity, η, of the jets in the laboratory frame for e^+e^- colliders (equivalent to the centre-of mass frame) and ep colliders. It can be seen that for a given rapidity, an order of magnitude smaller value of $x_\gamma^{\min}$ at THERA can be probed compared with HERA due to the increased electron beam energy, E_e. The minimum $x_\gamma^{\min}$ at TESLA would also extend the minimum possible at LEP and HERA. However, smaller values of $x_\gamma^{\min}$ can be reached at THERA than at TESLA in the very forward rapidity direction ($\eta_{LAB}^{ep} > 2$) reaching a minimum for this transverse momentum at $\eta_{LAB}^{ep} \sim 4.6$. This demonstrates that good forward detectors are needed for THERA with the ability to accurately reconstruct jets up to the rapidities discussed here. Only the e^+e^- TESLA collider is considered. The kinematic reach of the e^+e^- TESLA collider depends very much on the minimum required for the energy E_{tag} and angle θ_{tag} of the scattered electron. A much larger kinematic range could be covered with an $e\gamma$ collider based on TESLA [6]

Considering some restrictions in the detector layout, the values of $\hat{Q}^2$ obtainable are shown versus x_γ in Fig. 2b. Detectable scenarios for LEP and HERA are described in Fig. 2b and the same for TESLA and THERA are also imposed, although it is hoped that the future experiments would have improved detectors in the very forward and backward regions. Here it can be seen that although the e^+e^- machines will yield the lowest values of x_γ, it is also apparent that the ep machines can probe a smaller value of x_γ for a given $\hat{Q}^2$. In particular, THERA will provide valuable additional information on the structure of the photon in the region, $x_\gamma > 0.01$, particularly at high-p_T, complementing TESLA and the current experiments.

3 Summary

Photoproduction at THERA can further current knowledge of the structure of the photon, extending the current colliders, HERA and LEP and complementing the future linear e^+e^- collider program. The kinematic range can be extended, for quasi-real photons, in x_γ and the hard scale, $\hat{Q}^2 \sim p_T^2$. Also the structure of the virtual photon for larger square of its mass, Q^2, can be probed. Inclusive dijets, heavy quarks and prompt photons have been studied as
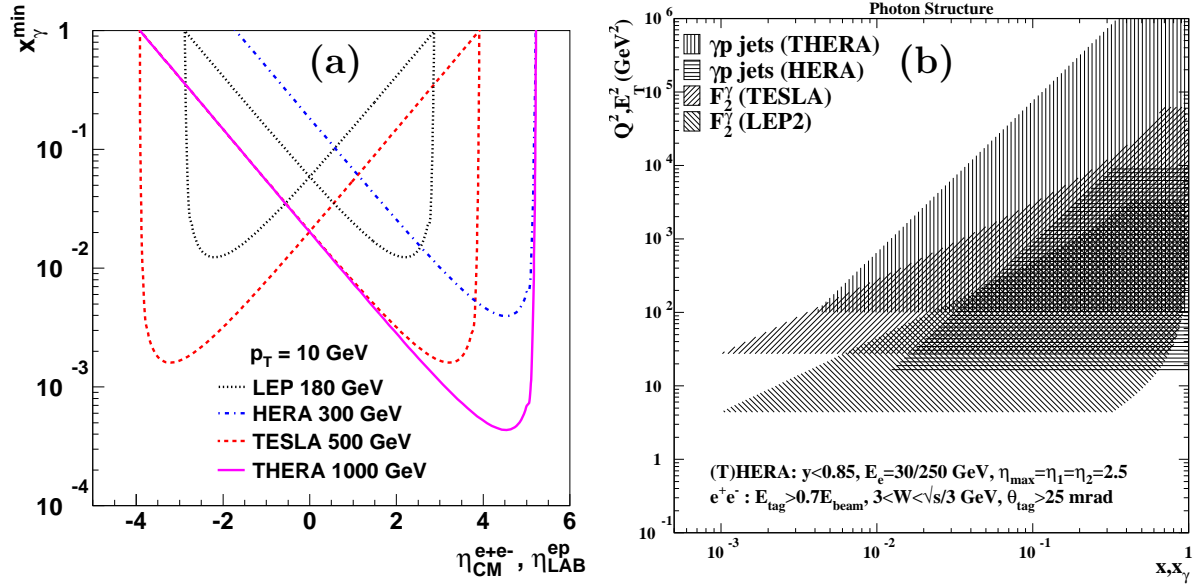
Figure 2: (a) The minimum photon momentum fraction, $x_\gamma^{\min}$, versus the rapidity of the jets in the centre-of-mass frame for e^+e^- machines and laboratory frame for ep machines. (b) Range in $\hat{Q}^2$ (Q^2 for F_2^γ or p_T^2 for γp jets) versus x_γ with realistic detector scenarios shown. The region for THERA is compared with that of TESLA, HERA and LEP.

tools to probe the structure of the quasi-real and virtual photon. The building of THERA will, therefore, enrich the field on the structure of a fundamental gauge boson - the photon.

Acknowledgements

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